LIDAR and Numerical Modeling Studies of Small-Scale Lateral Dispersion in the Ocean

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LONG-TERM GOALS

Our long-term goal is to better understand lateral mixing processes in the ocean on scales of 10 m to 10 km, i.e., the "submesoscale". We aim to understand the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. This research will contribute to fundamental knowledge of ocean dynamics at these scales, and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

OBJECTIVES

One objective of our work is to determine the extent to which shear dispersion – the interaction of vertical mixing with vertical shear – can explain lateral dispersion at scales of 10 m to 10 km. A second objective is to determine whether slow but persistent vortices enhance the stirring attributable to shear dispersion. We also share the overall objectives of the Lateral Mixing DRI to try to determine the extent to which submesoscale stirring is driven by a cascade of energy down (in wavelength) from the mesoscale, versus a propagation of energy upwards from small mixing events (e.g., via generation of vortices). A key technical goal of our work is to develop the use of airborne LIDAR surveys of evolving dye experiments as a tool for studying submesoscale lateral dispersion.

This annual report marks the end of year 5 of a 5 year study as part of the "Scalable Lateral Mixing and Coherent Turbulence" (a.k.a., LatMix) DRI. The main effort of the present work is a collaboration between J. Ledwell and E. Terray (WHOI), M. Sundermeyer (UMass Dartmouth), and B. Concannon (NAVAIR). This project is also being performed jointly with a collaborative NSF grant to J. Ledwell, E. Terray, and M. Sundermeyer (see "Related Projects" below). ONR support for this work included the airborne LIDAR operations as well as a substantial part of the field operations and analysis.

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APPROACH

Our approach is to release dye patches on an isopycnal surface in the seasonal pycnocline, and along the Gulf Stream front, and to survey their evolution for periods of 1 to 6 days, in collaboration with other investigators in the DRI. Two major field experiments have been conducted under the LatMix DRI, one 21 day experiment in the Sargasso Sea in June 2011, and one 25 day experiment along the north wall of the Gulf Stream in Feb/Mar 2012. Both efforts were multi-ship, multi-investigator efforts, of which the dye, drifter, and lidar work under this project were one part. Ongoing analysis of data from these field efforts is a collaborative effort between the field PIs, numerical modelers, and theoreticians.

In the context of the DRI modeling efforts, M. Sundermeyer is also collaborating closely with M.-P. Lelong in support of her DRI grant, "LES Modeling of Lateral Dispersion in the Ocean on Scales of 10 m – 10 km." As part of this, numerical simulations and analysis are being performed under the present effort in preparation for, and to aid interpretation of, the main field studies. These numerical simulations are also being coordinated with modeling efforts of other DRI participants.

WORK COMPLETED

A data analysis and planning meeting for the LatMix DRI was held in Palo Alto, CA in January, 2013, hosted by Stanford University. The main objectives of this meeting were to collaborate on ongoing data analysis relating to the June 2011 and 2012 field experiments, and to share results and enhance collaborations relative to data, modelling and theoretical analysis.

Descriptions of the experimental approach, the various components of both the 2011 and 2012 field experiments, and the roles of our numerous DRI collaborators, was provided in our FY2011 and FY2012 annual reports, respectively, and are not repeated here.

Major activities during the current reporting year have focused primarily on the 2011 field data analysis. Significant efforts during the current year include:

- Ongoing analysis of field data collected in June 2011
- Continued lidar data reduction and processing, including comparison w/ in situ data
- Development and refinement of lidar inversion algorithms
- Interpretation of major features of lidar-derived dye maps in the context of a variety of dispersion hypotheses

Specific objectives within the above major activities included the following:

- Generating geo-referenced maps of all lidar data, placed in context with the in situ observations
- Development and sensitivity studies of new inversion algorithms specific to the lidar system used in this study
- Continue collaborations with other field, modeling and theoretical efforts within the larger LatMix effort to determine underlying mechanisms of dispersion, including:

- Murray Levine (Oregon State University) who led the early in situ mapping of the fluorescein dye patches
- M.-Pascale Lelong (NorthWest Research Associates) conducting numerical simulations of internal waves and vertical motions to better understand potential driving mechanism of dispersion
- Eric Skyllingstad (Oregon State University) – conducting large eddy simulations of the ocean mixed layer to better understand the physics of the surface mixed layer release

As part of the modeling efforts in collaboration with M.-P. Lelong, we also continue to conduct numerical simulations pursuant to one of the hypotheses of the LatMix DRI, involving localized internal wave breaking and subsequent lateral stirring by the relaxation of diapycnal mixing events. We also continue to examine the effects of large-scale shears and strains, and of intermittency, on the vortical mode stirring mechanism. Additional manuscripts in preparation in collaboration with M. P. Lelong and her student, J. Jacobs, are described in Dr. Lelong's annual report. Overall, the purpose of these simulations is to help guide our interpretation of the field data in distinguishing among different possible lateral mixing processes.

RESULTS

A total of nine dye release experiments were conducted during the June 2011 field effort, two 6-day rhodamine experiments, and seven 26-36 hr fluorescien experiments. The dye studies were focused on the upper ocean, primarily within the seasonal pycnocline, so as to enable the study of stratified interior waters, but relatively near the surface to enable lidar penetration into the dye layer. One fluorescein experiment was also conducted in the surface mixed layer. Mixed layer depths were typically 10 to 20 meters, but varied from virtually zero to as much as 25 m, depending on wind and radiative conditions, and on location with respect to ocean fronts. Drifters with surface buoys and drogues set for approximately the depth of the dye patches were also released with the dye. Nine drifters were deployed in a cross pattern centered on the dye streak for the longer-term (~140 hr) rhodamine experiments, and two or three along the streak for each of the short-term (~36 hr) fluorescein experiments, giving as many as 18 drogues in the water at any given time.

A description of the two 6-day rhodamine experiments was provided in our 2011 annual report. Here we focus on the fluorescein experiments, with particular emphasis on the lidar observations associated with these experiments. Summary plots of the dye evolution for the various experiments observed via airborne lidar are shown in Figs. 1-7. Major features are described in the following paragraphs.

June 10, Fluorescein Experiment 4:

An overview of the June 10 fluorescein experiment is shown in Figs. 1 & 2. Major features are the elongation of the patch in the north-south direction, consistent with the observed velocity shear at the depth of the dye (Fig. 1 velocity profiles, and upper panels in Fig. 2). Visual inspection of the depth of the peak lidar return (lower panels in Fig. 2) suggests that the deeper portion of the dye was sheared off to the northeast compared to the main dye streak (evident as narrow band of strong signal at southwest tip of patch in Fig. 2). Also evident is a broad sinuous meander of the patch early in the evolution (3.1 hrs), as well as evidence of filamentation on the eastern edge of the patch throughout the surveys (enhanced signal on right edge of patch in all surveys, extending from lower third to middle of patch). Both of these features suggest the possibility of weak small-scale (<1 km) differential lateral advection

acting on the patch. Finally, late evolution of the patch (6.3 hr) indicates a SW-NE oriented banding of the dye with wavelength of order 100 m, while the depth of the peak return (lower row in Fig. 2) shows banding oriented in the NW-SE direction. Whether this banding is the signature of internal waves, or surface waves (swell) is under investigation.

June 15, Fluorescein Experiment 5:

An overview of the June 15 fluorescein experiment is shown in Figs. 3 & 4. Two complete surveys, plus a third incomplete survey of the patch reveal an extremely rich structure in the dye evolution for this experiment. Major features include the finger-like structures stretching westward relative to the main patch, as well evidence of the development of filamentation along both the southern and eastern sides of the patch. The fingerlike structures stretching westward appear to be consistent with variations in potential density along the track of the injection line (not shown), and hence are thought to be the result of dye being injected across internal wave crests and troughs, i.e., the injection was not perfectly along a single isopycnal. This variability of the injection enabled a mean westward differential advection of dye at shallower isopycnal depths relative to deeper, denser isopycnals. The extent of this differential advection is roughly consistent with the depths of the peak returns (lower panels in Fig. 4), as well as with mean westward shear estimated via shipboard ADCP measurements. That these fingerlike structures persisted for more than 5 hours after the injection, despite their relatively small scale (order 50 m), suggests an upper limit on the lateral dispersion acting on these scales. Meanwhile, the 100-200 m scale filamentation observed at the southern most extent of the patch, as well as the 300 m scale curvature at the northeastern-most end of the patch both again suggest some degree of small-scale differential advection acting on the patch. Last, we again observe some suggestion of NW-SE oriented banding in the depth of the peak return (lower panels in Fig 4), although not nearly as pronounced as in the June 10 experiment (compare Figs. 2 and 4).

June 16, Fluorescein Experiment 6 and 6a:

The June 16 dye release consisted of both a pycnocline and a surface mixed layer release, the latter performed immediately following and along the same ship heading as the former. The two patches from the June 16 experiment are shown in Figs. 5-7. Considering first the deeper pycnocline release, three partial surveys of the patch show a broad widening of the patch, again with some evidence of small-scale structure / filamentation along the southwestern edge of the patch (Fig. 6, upper panels). Meanwhile, depths associated with the peak lidar returns (lower panels in Fig. 6) show evidence of banding of the depth of peak return oriented in the NNW-SSE directions.

Meanwhile, the surface mixed layer portion of the patch, seen in Fig. 5 to rapidly separate from the deeper patch, shows a rich structure of large eddy circulation within the mixed layer. As evident in Fig. 7, the surface portion of the patch rapidly (over the first 0.25 – 1.6 hrs) develops a banded structure oriented in the SW-NE direction, as it is advected downwind (SW). The banding has a wavelength of order 100 m, with deep (20 m, roughly the base of the mixed layer) tails extending upwind relative to the more rapidly advected surface (within a few m of the surface) portions of the patch. Given these characteristics, this banding appears to be consistent with some form of large eddy circulation across the depth of the mixed layer.

Ongoing Work on Lidar Inversion:

As the present project represents our first major field experiment using airborne lidar to survey dye release experiments (following a proof of concept experiment performed under separate funding in 2004), a significant part of our effort continues the development and calibration of algorithms to invert the raw lidar signal (Watts) to absolute dye concentration (ppb). Given the particular characteristics of the lidar system used in the present study (signal to noise in the backscatter vs. fluorescence channels, lidar system parameters, etc.), our approach for the present work is to use a forward model of the lidar signal and system characteristics, accounting for seawater attenuation, to invert for the dye concentration profile using nonlinear regression. An example of a synthetic dye concentration profile together with the forward backscatter and fluorescence waveforms are shown in Fig. 8, alongside a sample of the actual lidar data collected during the June 15 fluorescein dye experiment. Significant effort has been spent over the current project year testing this as well as alternate models, as well as verifying the values of relevant system parameters and how they are best incorporated into the present model.

Analysis and interpretation of the dye distributions shown in the above figures, together with other data collected during the June 2011 field experiments continue to be ongoing, both under the current project, as well as the collaborative NSF effort cited below. Key outcomes for the current reporting period are as follows:

- Lidar derived maps of dye from 0.25 – 6 hrs after dye injection reveal a rich structure of dye and dye dispersion in the seasonal pycnocline and surface mixed layer
- To date we have identified and interpreted numerous key features associated with the dye evolution, including:
    - Overall advection and spreading of the dye patches
    - Evidence of vertical shearing of the patches
    - Streamers emanating from the main injection line, presumed to be associated with injection across different isopycnals
    - Signatures of surface and/or internal waves in both the peak dye returns and the depths of the peak returns
- We have found evidence of small-scale stirring on scales of the dye patches, more so in some (e.g., June 15) than other of the experiments (e.g., June 10 & 16)
- We have identified clear evidence of artifacts of the injection (especially evident in June 15 experiment), suggesting room for improvement in future work
- Dye distributions will enable upper bounds of both diapycnal and lateral dispersion to be estimated – this includes bulk moments of the dye patches, as well as upper-bounds estimates of smaller-scale dispersion from streamers (e.g., June 15)
- A surface mixed layer experiment shows evidence of large eddy overturning within mixed layer associated with the gradual deepening of the m.l. Tails of the dye patch at the base of the mixed layer suggest rapid deepening of the surface injection, while persistence of these tails suggests an upper bound on diapycnal mixing, and/or possible subduction below base of mixed layer.

IMPACT/APPLICATIONS

The present work uses a novel approach – remote sensing of dye using airborne lidar – to study mixing in the ocean. Our research will contribute to fundamental knowledge of ocean dynamics at the "submesoscale", and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

RELATED PROJECTS

The above work and findings represent a joint effort on the part of LatMix DRI PIs Ledwell and Terray (WHOI) and Sundermeyer (UMass Dartmouth) under ONR grants N00014-09-1-0175 and N00014-09-1-0194, respectively, and Brian Concannon (NAVAIR) under ONR award N0001411WX21010. Furthermore, our work is coordinated with all the other projects within the Lateral Mixing DRI.

Field instrumentation used in the 2011 field work was purchased in part under DURIP grant N00014-09-1-0825, and in part under a related NSF project entitled "Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline", NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI). The PIs efforts under the ONR LatMix DRI are being performed in coordination with the PIs efforts under the above mentioned NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

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Brunner-Suzuki, A.-M., M. A. Sundermeyer and M.-P. Lelong, 2012. Vortical modes, internal waves, and inverse energy cascades. Submitted to *J. Phys. Oceanogr.*.

FIGURES

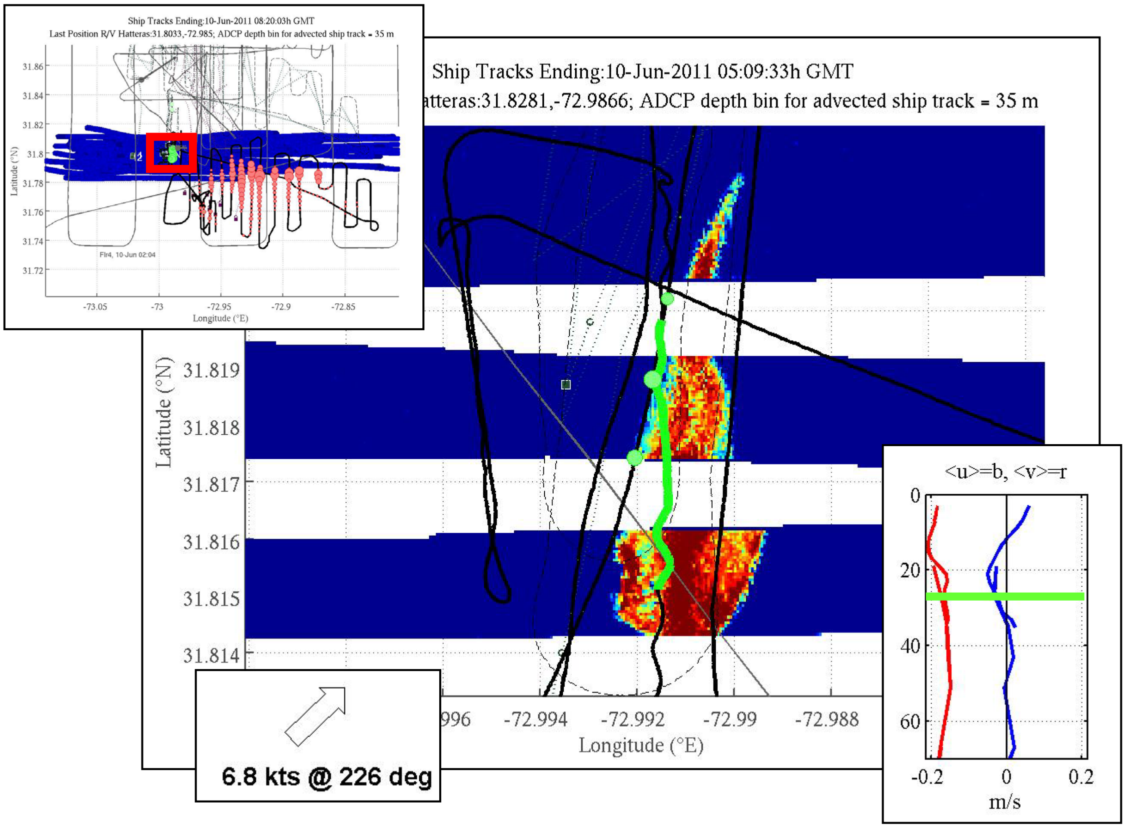

Fig. 1. Main panel: Plan view maps of ship track (bold black line), injection line (bold green line), and peak lidar returns (false color image) observed during overflights of June 10 fluorescein dye experiment approximately 3 hrs after release. In situ survey profiles where dye was found are shown (for context) as green circles. Upper left inset: Location of fluorescein patch relative to larger June 6 rhodamine dye release experiment. Lower left inset: Mean wind speed during injection and surveys. Lower right inset: Mean u, v velocity profiles from R/V Hatteras shipboard ADCP (150 and 600 KHz) averaged over the time of the lidar surveys, with bold green line indicating dye injection depth.

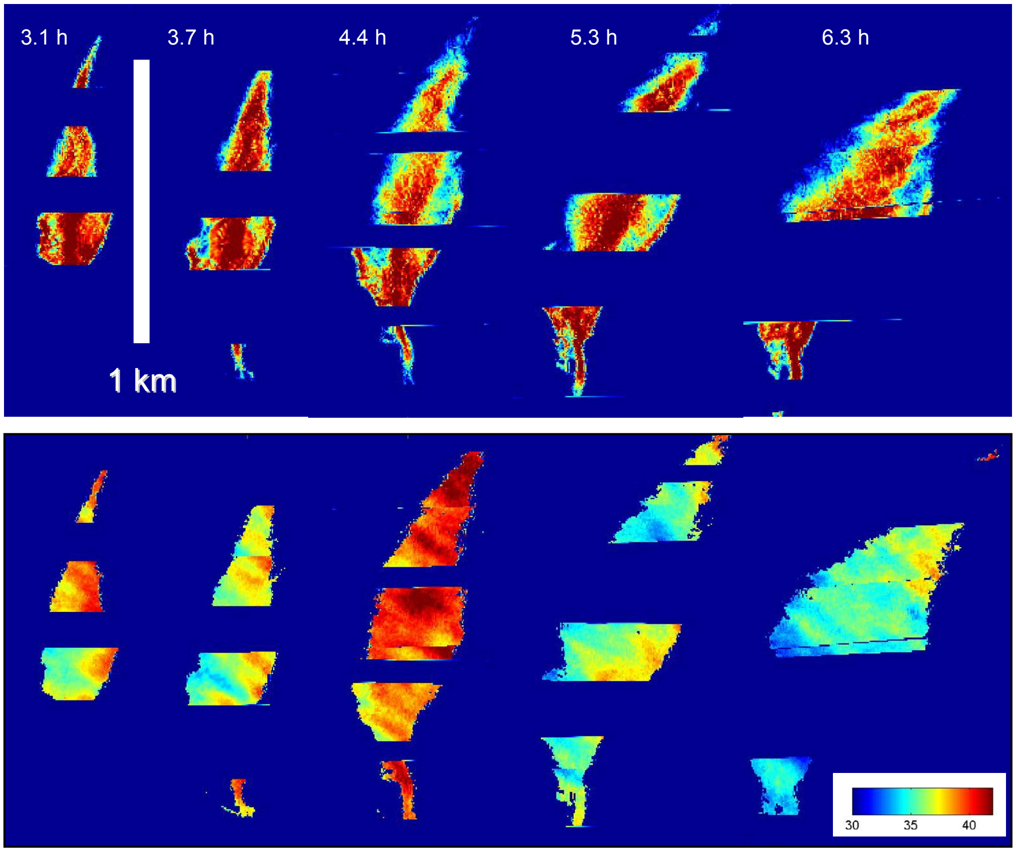

Fig. 2. Plan view maps of lidar-derived dye signal showing evolution of the June 10 fluorescein patch over the course of the lidar surveys. Time evolution goes from left to right, with time since injection indicated above each survey. Upper panels are lidar peak intensity return (Watts). Lower panels are depth (m) of peak return for same times

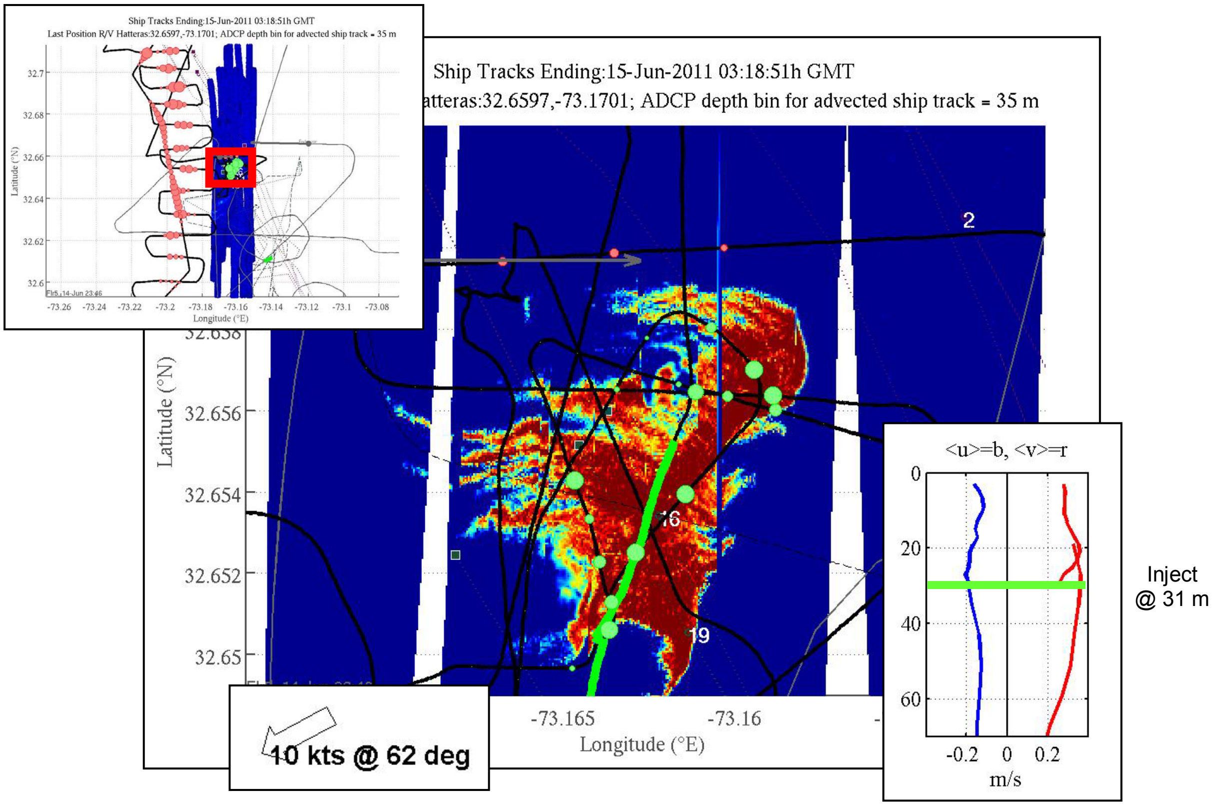

Fig. 3. Similar to Fig. 1, but for June 15 fluorescein dye experiment approximately 3.5 hr after release.

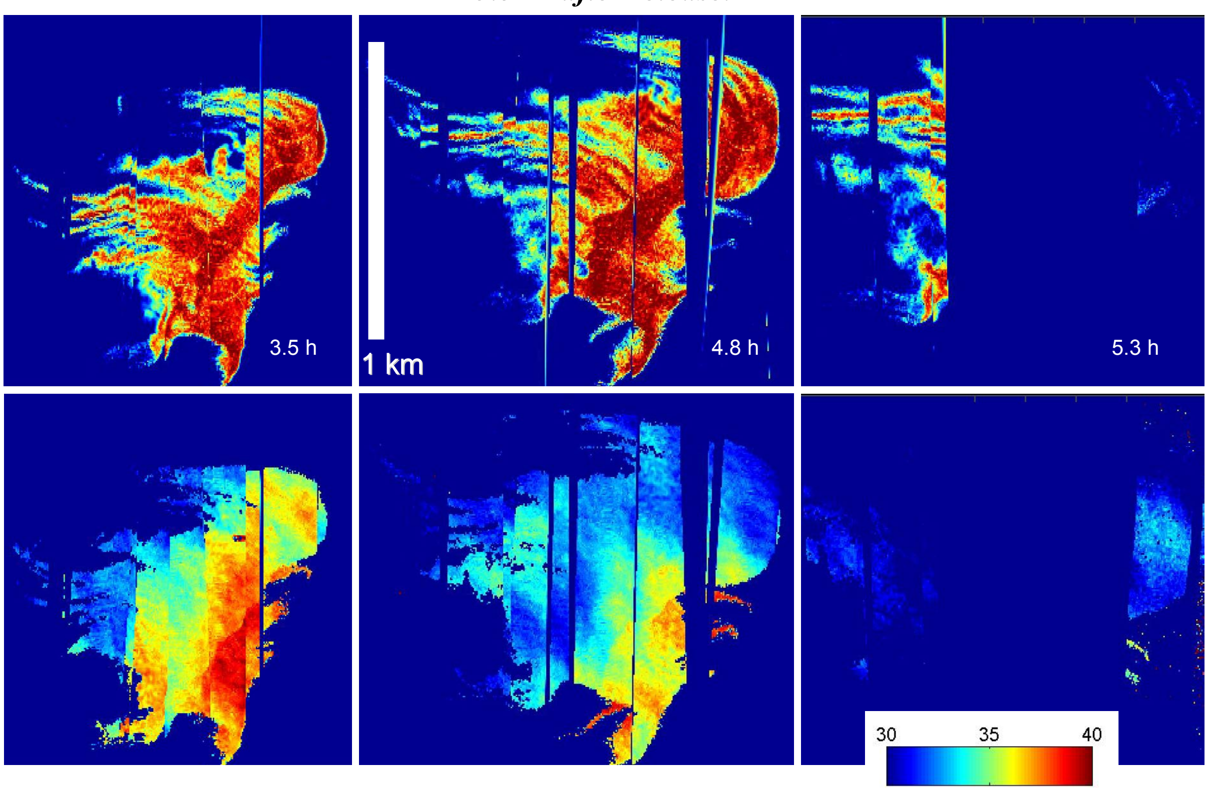

Fig. 4. Similar to Fig. 2, but for June 15 fluorescein patch.

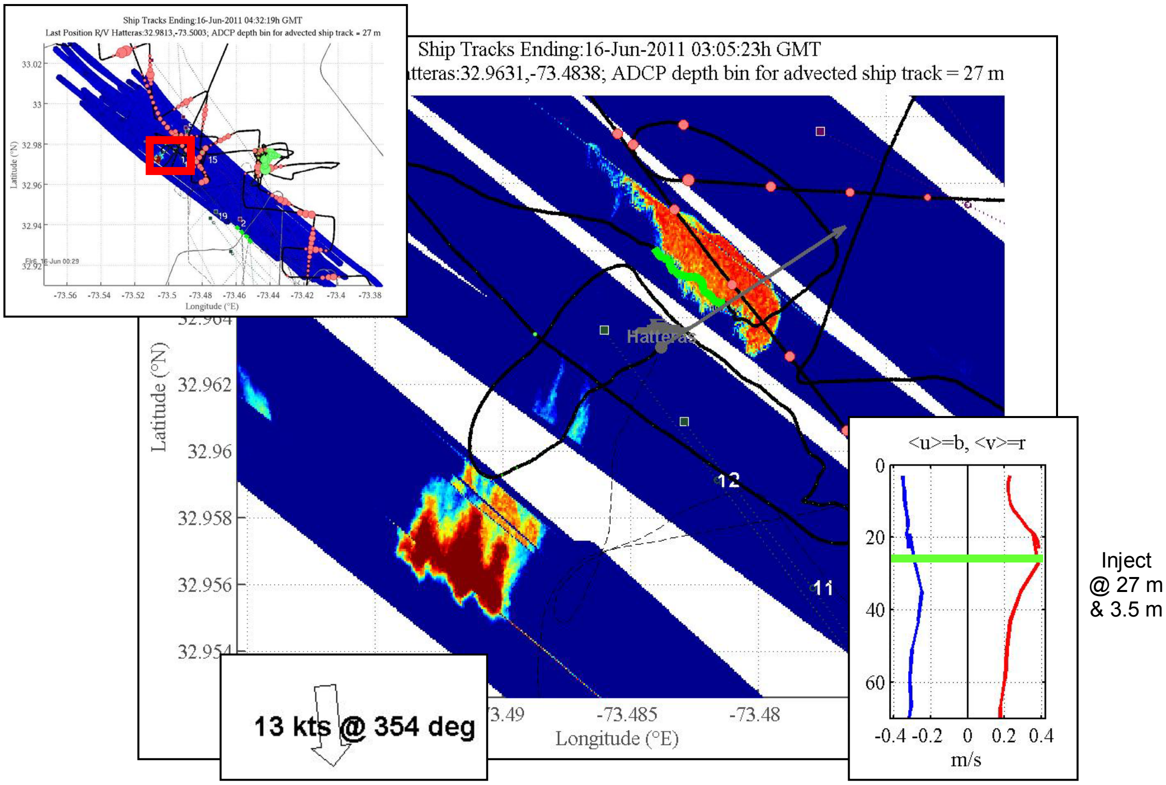

Fig. 5. Similar to Fig. 1, but for June 16 fluorescein pycnocline (NE patch of dye in main panel) and surface releases (SW patch of dye in main panel) 2.6 and 1 hrs (respectively) after release.

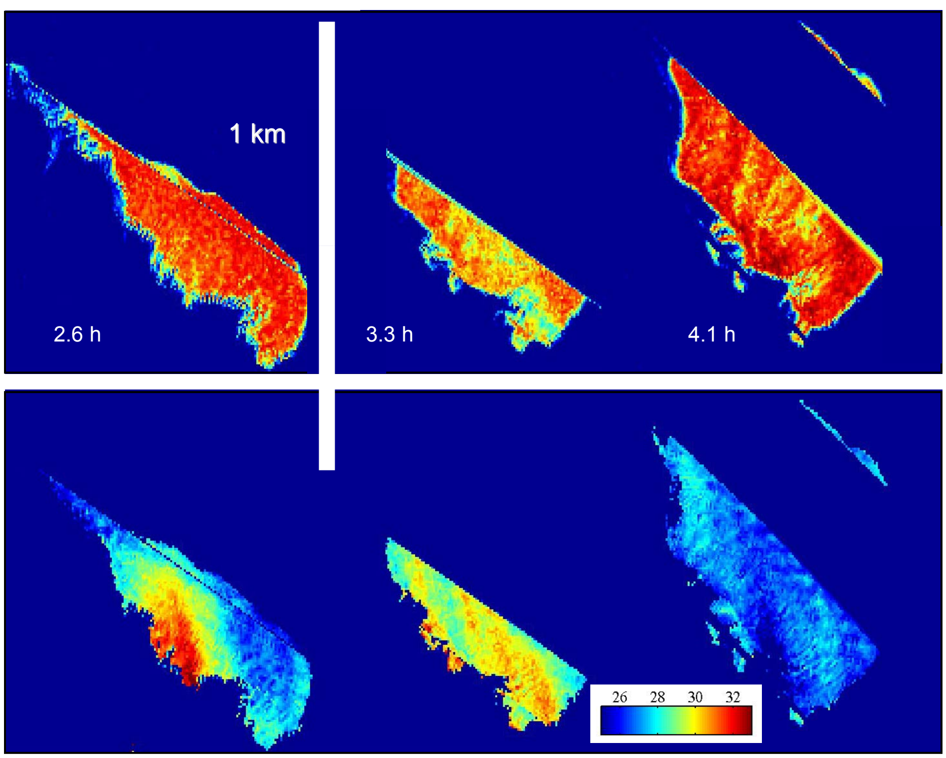

Fig. 6. Similar to Fig. 2, but for June 16 seasonal pycnocline fluorescein patch.

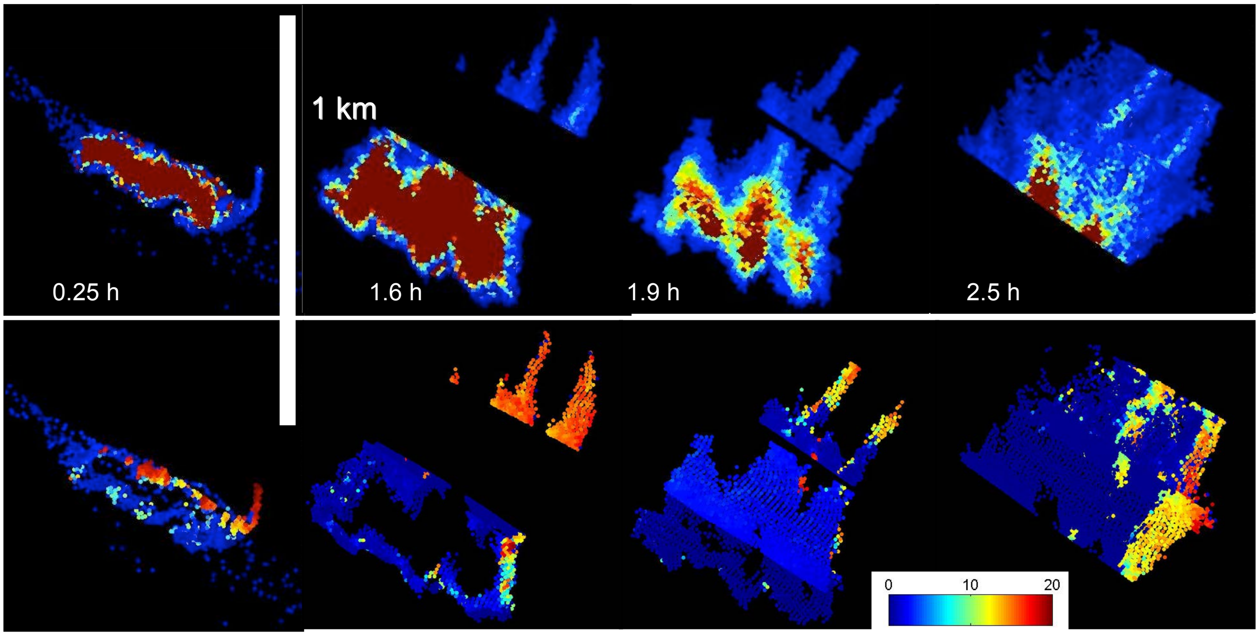

Fig. 7. Similar to Fig. 2, but for June 16 surface mixed layer fluorescein patch.

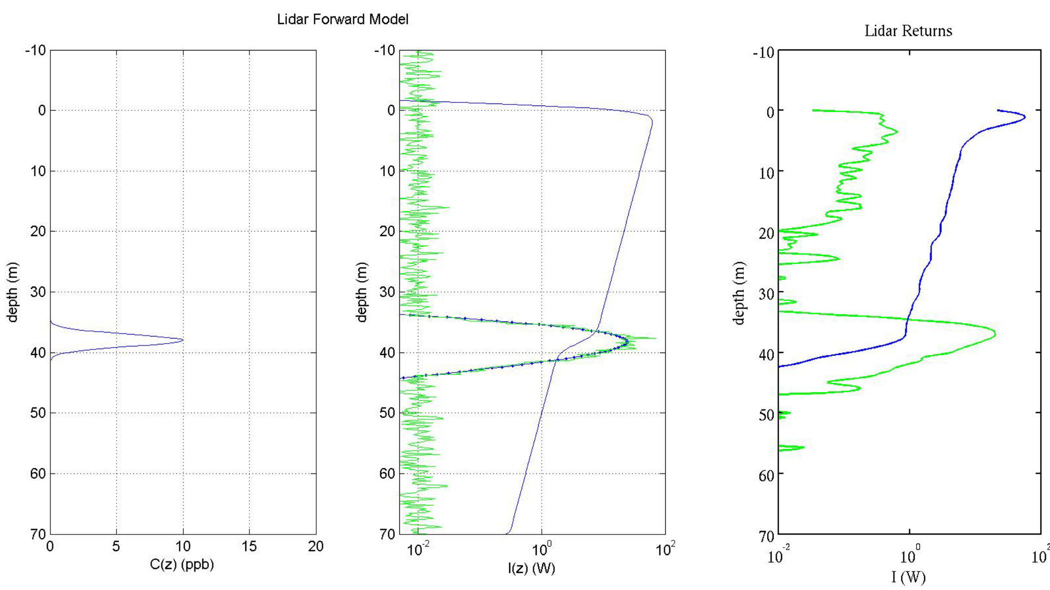

Fig. 8. Left panel: Synthetic dye concentration profile (ppb); middle: fluorescence + noise (green) and backscatter (blue) returns from lidar forward model; and right: fluorescence (green) and backscatter (blue) signals from actual observed lidar returns.